Field Determinations of Surface Emissivity and Temperature for Lake Ontario

J. A. DAVIES, P. J. ROBINSON AND M. NUNEZ

Dept. of Geography, McMaster University, Hamilton, Ontario, Canada

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ABSTRACT

Field determinations of surface emissivity and temperature were carried out at the western end of Lake Ontario between July and November 1969. Emissivity was obtained from infrared thermometer measurements using an aluminum cone. Surface temperature was measured directly with floating thermistors and estimated from outgoing longwave radiation.

Emissivity was constant at 0.972 with no detectable variation with water turbidity and chemical content changes. Float and infrared thermometer temperatures were in good agreement at times when there were no sensor problems. Temperatures calculated from the radiation balance agreed well at night with the other methods but showed irregular fluctuations and systematic overestimation during daytime probably due to errors in determining outgoing longwave radiation. Comparison with float data over the experimental period showed temperature differences ΔT with a change of sign in September corresponding to a sign change in the difference between air and water surface temperatures. Both the sign and order of magnitude of ΔT may have been due to divergence of the upward longwave radiation flux.

1. Introduction

Surface temperature exerts considerable control over important physical processes at the earth-atmosphere interface. It influences the surface radiation balance by way of the Stefan-Boltzmann law which provides the direct link with emitted longwave radiation. Since it also sets the boundary condition for vertical mass transfer of sensible and latent heat, it affects the surface energy balance.

Surface temperature measurement is difficult and little data have been collected compared with atmospheric or sub-surface temperature data. Vertical temperature gradients can be large at the interface between air and water. The use of conventional contact thermometry is hindered by the difficulty of defining this interface and locating sensors with minimal surface interference. In addition, the measured temperatures include radiation errors even with small sensors. Remote sensing with an infrared thermometer avoids these difficulties but surface irradiance and emissivity must be known if temperature is to be determined to within an accuracy of 0.3°C (Fuchs and Tanner, 1966).

This paper discusses surface temperature and emissivity results from studies carried out over Lake Ontario between July and November 1969. These formed part of a large study of radiation balance components. Attempts were made to measure surface temperature by different methods of varying complexity which might be useful in future short-term or long-term studies from lake towers, buoys or vessels.

Spot determinations of emissivity were also made at selected times during the program. Although previous work (e.g., Buettner and Kern, 1965) has shown that the emissivity of water is between 0.95 and 1.0, few determinations have been published.

Field measurements were carried out from and near an instrumented tower at the western end of Lake Ontario. The tower was located in shallow water (4 m deep) approximately 400 m from the shore.

2. Determination of surface temperature and emissivity

a. Surface temperature

Surface temperatures were determined by three procedures: 1) direct measurement with float-borne thermistors, 2) indirect evaluation with an infrared thermometer, and 3) indirect evaluation from emitted longwave radiation from the lake surface.

Two styrofoam floats with attached thermistors were constructed. One consisted of an anchored square float (12 cm²) with a single thermistor threaded through a central hole drilled in the styrofoam. The thermistor was wired into a stepping switch on the tower. From this a cable was led along the lake bed to a recording station on shore. All temperature signals were recorded on a potentiometric strip-chart recorder (Hewlett-Packard Model 7100B) to an accuracy of 0.2% of full scale. Hence, in principle, temperature was obtained to within $\pm 0.14^\circ\text{C}$ which corresponded approximately with the resolution (0.18°C). This system was used

continuously throughout the field season, except for a four-week period in late July and August. The second device used five thermistors. Four were placed at the centers of the sides of a square aluminum frame equipped with styrofoam floats at the corners. A fifth was placed in the center of the frame. All thermistors were matched and calibrated before and after the project. The float could only be used satisfactorily on two days with relatively calm conditions. The sensors on both floats were set as close to the water surface as possible.

On three occasions an infrared thermometer (Barnes Engineering Co., Model PRT-5), was used to obtain surface temperatures close to the floats. The measurements were made from the tower platform, 4 m above the water surface. This sensor measures surface infrared radiation within the 8–14 μ wavelength interval set by its bandpass filter. The corresponding blackbody temperature is given directly. A correction is required since natural surfaces approximate grey bodies. The flux incident on the sensor is the sum of the emitted and reflected intensity from a surface which can be expressed as

$$C_1\sigma T_r^4 = C_2\epsilon\sigma T_s^4 + (1-\epsilon)C_3L_i, \quad (1a)$$

in which T_r is the apparent surface temperature measured directly with the infrared thermometer, T_s the true surface temperature, L_i the incident longwave radiation, ϵ the surface emissivity (assumed constant with wavelength), and σ the Stefan-Boltzmann constant [0.817×10^{-10} cal cm⁻² min⁻¹ (°K)⁻⁴]. The constants C_1 , C_2 and C_3 define the fraction of total blackbody radiation that is transmitted by the filter. Although these depend on temperature, they can be assumed equal since the usual range of temperatures is small. Hence

$$\sigma T_r^4 = \epsilon\sigma T_s^4 + (1-\epsilon)L_i, \quad (1b)$$

and from (1b)

$$T_s = \{[\sigma T_r^4 - (1-\epsilon)L_i]/\epsilon\sigma\}^{\frac{1}{4}}, \quad (2)$$

The determination of emissivity will be discussed in a later section. Incoming longwave radiation was obtained from

$$L_i = T_i - S_i, \quad (3)$$

in which T_i is the incident total (longwave and shortwave) radiation, and S_i the global radiation; the latter was measured continuously with an Eppley pyranometer (Eppley Laboratory Inc.), while total radiation was evaluated using a polyethylene-shielded net radiometer (Swissteco Pty. Ltd., Melbourne) with the lower thermopile surface enclosed within a blackbody cavity. The cavity temperature was monitored with a thermistor. Total radiation was obtained from

$$T_i = T_i' + \sigma T_e^4, \quad (4)$$

in which T_i' is the apparent total radiation as measured

directly by the Swissteco instrument and T_e the temperature of the blackbody cavity. The third method of evaluating surface temperature used the Stefan-Boltzmann law to convert known outgoing longwave radiation. Given measurements of net radiation R_n and reflected solar radiation S_0 in addition to total radiation, we have

$$T_s = \{[L_0 - (1-\epsilon)L_i]/\epsilon\sigma\}^{\frac{1}{4}}, \quad (5)$$

in which L_0 is the outgoing longwave radiation ($=T_i - R_n - S_0$), R_n being the net radiation (all wavelengths), and S_0 the reflected solar radiation from the surface. Eq. (5) is essentially the same as (2) except that measured L_0 replaces the apparent surface radiative flux calculated from infrared thermometer measurement. An inverted Eppley pyranometer and a Swissteco net radiometer were used to measure S_0 and R_n .

b. Surface emissivity

Emissivity is defined as the ratio of radiation emitted by a surface at a given temperature to the blackbody radiation at the same temperature. It depends upon both wavelength and direction of emission, but is usually referred, for a given wavelength, to the normal to the surface. Integrated over all wavelengths, it is defined by rearranging (2) and replacing L_i with σT_k^4 , i.e.,

$$\epsilon = (T_r^4 - T_k^4)/(T_s^4 - T_k^4), \quad (6)$$

in which T_k is the radiative temperature of the sky. These measurements can be made with an infrared thermometer. The emissivity thus determined refers to the wavelength interval of the sensor bandpass but it is assumed that this will be the same for the entire longwave portion of the spectrum.

Several methods have been used in previous work to obtain σT_k^4 . Buettner and Kern (1965) placed a surface of known emissivity and temperature above the test surface and then calculated L_i . Fuchs and Tanner (1966) used a reference surface of known emissivity and temperature placed on the ground close to the test surface. This method permits the calculation of L_i from $(1-\epsilon)L_i$. Lorenz (1966) sampled sky radiation in several directions and integrated the results to obtain total radiation from the whole hemisphere. An approach similar to that of Lorenz was used in this study, since the other methods were not practical on a lake surface. Sky radiative temperatures were determined from several directions and a representative value T_k was assigned. Variations were rarely greater than 1°C.

Measurements of T_r were obtained by directing the Barnes sensor at the lake surface. Measurements of true surface temperature T_s were made by isolating the surface from sky radiation and allowing it to radiate as an apparent blackbody. Following a method described by Fuchs and Tanner (1968), an aluminum

cone was placed over the water and the surface radiation measured through a hole at the apex. The inner surface of the cone was polished to reduce its emissivity. It could then be assumed that its temperature was close to that of the water surface. Fuchs and Tanner (1968) showed that even if the temperature difference between the inner cone surface and the water surface was as large as 10C, the error in determining T_s was only 0.2C, which is within the limits of accuracy of the thermometer.

The cone was supported on two fine wires stretched on a square float such that its rim was slightly below water level. Several holes were drilled in the cone near the rim to allow water movement and to ensure a constant level water surface. The supporting wires were inconspicuous since they were of fine gage and located several centimeters below the water surface.

Measurements were made in the sequence: T_k , T_r , T_s and T_k again. When the cone was in place there was a period of ~ 20 sec in which the reading of T_s was constant. Thereafter, the temperature rose appreciably as the surface energy balance was altered. During calm conditions, placing of the cone, temperature reading and cone removal could be accomplished in about 10 sec. The sequence took longer with a light swell. The method was not practical with wave heights ≥ 25 cm. On most occasions measurements were taken within 3 m of the dock. Each set of measurements was repeated at least three times with a pause of 1 min between each set to allow re-establishment of the normal energy balance. This period of time was required in calm conditions but in other conditions readjustment of the energy balance was more rapid, presumably because of more rapid water mixing.

Measurements were made under both clear and cloudy skies. In some instances, under the former, T_k could not be determined accurately since the temperatures for almost the whole hemisphere were beyond the lower limit of the radiometer scale (-20°C). These data were discarded. On days with complete overcast this problem did not arise and the most reliable results were probably obtained under these conditions. Measurements of T_k could not be made easily when cloud cover was changing constantly. However, a substantial error in T_k can be tolerated. Differentiation of (6) with respect to T_k yields

$$\frac{\delta\epsilon}{\delta T_k} = 4T_k^3(T_r^4 - T_s^4)/(T_s^4 - T_k^4)^2. \quad (7)$$

Using typical temperature values ($T_r = 22^\circ\text{C}$, $T_s = 23^\circ\text{C}$, $T_k = -20^\circ\text{C}$), the variation in emissivity with T_k is $0.001(^\circ\text{C})^{-1}$, which is negligible. A 10C error in determining T_k results in an error of 0.01 in emissivity. Similarly, differentiating (6) with respect to T_r and T_s , and using the same temperature data, shows that the variation in emissivity with T_r is $0.028(^\circ\text{C})^{-1}$ and

$-0.026(^\circ\text{C})^{-1}$ with T_s . Greater accuracy, therefore, is required in the determination of these temperatures.

3. Results

a. Surface emissivity

The results of the field determination of emissivity are shown in Table 1. The narrow range of values (0.952–0.989) has a mean and standard deviation of 0.972 and 0.021. Although cloud type and amount and sky temperature varied considerably between days, there is no significant change in surface emissivity values. On four occasions (A,B,C,D in Table 1) measurements were made at both the tower and the dock sites within a few minutes of each other. The dockside water was noticeably more turbid on these occasions but differences in emissivity were within the experimental error of the method and less than the overall standard deviation.

Chemical composition of the lake water was determined from surface samples taken on seven occasions near times of measurement (Table 2). No significant relationship with emissivity could be found. Anderson (1954) reported a similar finding from Lake Hefner data. This result is not surprising since longwave radiation penetrates a very small distance into water and unless particulate and chemical content have surface expression, there can be no effect upon surface emissivity.

The mean emissivity value of 0.972 agrees closely with Anderson's value of 0.97. It would seem that 0.97 may be a suitable value to apply to all freshwater bodies except where films of foreign substances, such as oil, are present. There was no opportunity to determine such effects during the project but significant deviations from this mean emissivity value may occur. It is, therefore, relevant to consider the effect of an error in assigning a value for emissivity. The effect depends on whether the assigned emissivity is used to compute emitted longwave radiation or surface temperature. Emitted longwave radiation L_0 from a surface is related to surface temperature through the Stefan-Boltzmann law, i.e.,

$$L_0 = \epsilon\sigma T_s^4, \quad (8)$$

from which surface temperature is given as

$$T_s = (L_0/\epsilon\sigma)^{1/4}. \quad (9)$$

Thus, an error of a few percent in ϵ will result in an error in L_0 of the same amount. Hence, the commonly assumed value of unity for the emissivity of water introduces negligible error ($< 3\%$) in emitted radiation calculation. Provided that surface temperature is measured with reasonable accuracy, radiation calculations from (8) will be more accurate than measurements with currently available radiometers.

TABLE 1. Emissivity values for Lake Ontario.

Date (1969)	Local time	Site*	T_a (°C)	T_s (°C)	T_r (°C)	Cloud Type	Amount (tenths)	Emissivity** ϵ	Dock ϵ minus tower ϵ
15 September	1430	D	-25.0	19.3	18.5	Ac Cu	4	0.977	
	1630	D	-20.5	20.5	19.7	Ac	4	0.976	
16 September	1240	D	-10.0	19.7	18.7	As Ac	9	0.961	
22 September	1130	T	-23.0	13.9	13.2	Clear	0	0.977	
	1330	T	-23.0	15.8	14.9	Clear	0	0.972	
25 September	1220	D	+7.0	15.0	14.7	Sc	10	0.961	
26 October	1660	D	0.0	9.4	9.3	As Ac	10	0.989	
	1650	D	-8.0	9.0	8.8	As Ac	9	0.987	
27 October	1230	D	-5.5	8.1	7.9	Sc	9	0.984	
	1350	D	-6.5	8.0	7.6	Sc	9	0.970	
	1640	D	-7.5	6.7	6.4	Sc	10	0.977	
	1770	D	-5.5	7.7	7.4	Sc Ac	10	0.976	
28 October	1200	D	-25.0	8.0	7.0	Ac	1	0.964	
	1515	D	-25.0	8.0	7.0	Ac Cu	2	0.964	
3 November	1210	T	-20.0	8.8	8.3	Ac Sc	8	A 0.980	0.005
	1230	D	-12.0	9.8	9.5	Ac Sc	8	0.985	
	1400	D	+1.5	10.5	10.3	As	10	B 0.977	0.009
	1410	T	-9.0	8.0	7.5	As	10	0.968	
	1505	D	+8.0	10.1	10.0	As	10	C 0.952	-0.020
	1520	T	0.0	7.5	7.3	As	10	0.972	
4 November	1025	T	-7.0	8.0	7.5	As Ac	9	D 0.964	0.004
	1040	D	0.0	9.8	9.5	As Ac	10	0.968	
	1330	D	-8.0	9.5	9.0	As Ac	9	0.969	
	1610	D	-20.0	9.5	9.0	As Ac	9	0.980	
5 November	1010	D	-15.0	7.5	7.0	Ac Cu	9	0.975	
	1315	D	-20.0	8.0	7.5	Cc Ac Cu	4	0.979	
	1505	D	-2.0	10.0	9.5	As Sc	10	0.956	

* D, dock; T, tower.

** See text for discussion of cases A, B, C, D.

Calculated values of surface temperature from (9), however, are much more sensitive to changes in emissivity. For values of L_0 between 0.53 and 0.65 cal $\text{cm}^{-2} \text{min}^{-1}$, a 0.01 change in emissivity produces a temperature change of 0.7–0.8°C (Table 3). A 3% error in emissivity (1.00 as opposed to 0.97) produces substantial errors of 9–19% in calculated surface temperature. Moreover, these are minimal errors. Others arise from uncertainty in the value of σ and in evaluating the emitted radiation. Since measured longwave radiation from a surface includes a reflected sky component, $(1-\epsilon)L_i$ should be subtracted from the right-hand side of (9). Although this approach offers the advantage of permitting surface temperature evaluation from remote measurements, the possibility of large errors may limit the usefulness of the results in energy balance studies.

b. Surface temperature

Simultaneous measurements of surface temperature by the four methods outlined previously were made over a 24-hr period from 1600 on 16 July to 1700 on 17 July (Run 1). The results from the single-sensor float are treated cautiously since five days later moisture leakage was detected in the signal cable. Both sensor and cable were replaced. Measurements did not resume until 27 August. A second 24-hr run (Run 2) was made without the single-sensor float between 30 July and 31 July.

During the two 24-hr runs three of the four surface temperature determinations were obtained from continuous strip-chart records. Spot infrared thermometer measurements were made from the tower platform at

TABLE 2. Variation of emissivity with water conditions.

Date (1969)	Time	Site	Emissivity	Ortho-phosphate (ppm)	Nitrite plus nitrate (ppm)	Dissolved solids (ppm)	Suspended solids (ppm)	Dissolved oxygen (mg liter ⁻¹)
28 October	1515	D	0.964	37	230	220	700	—
3 November	1515	T	0.972	0	164	205	446	12.9
3 November	1530	D	0.952	9	100	207	466	11.2
4 November	1605	D	0.980	9	148	215	456	12.7
5 November	1020	D	0.975	0	144	204	522	11.7
	1330	D	0.979	—	—	—	—	11.7
	1515	D	0.956	1	148	220	92	12.1

TABLE 3. Effect of emissivity changes upon calculated surface temperature (°C).

Emissivity	L_0 0.53	% error	L_0 0.57	% error	L_0 0.61	% error	L_0 0.65	% error
1.0	10.6	-16.9	15.4	-14.4	20.8	-9.2	25.4	-8.0
0.972	12.6	—	18.0	—	22.9	—	27.6	—
0.96	13.5	7.1	18.8	4.4	23.8	3.9	28.5	3.3
0.95	14.3	13.5	19.6	8.9	24.2	5.7	29.3	6.2
0.94	15.0	19.0	20.3	12.8	25.4	10.9	30.2	9.4

approximately 2-hr intervals by pointing the sensor manually at the water surface near the tower and taking a visual reading. The results, plotted in Fig. 1, show the best agreement (to within 1–2°C) between the several methods in late afternoon, night and early morning. From 0500 in both runs there is poorer agreement. Here the infrared thermometer data will be considered as standard. The mean of the five measurements from the multiple sensor float during Run 1 gives results to within 1°C in the morning hours until noon but differences increase to a maximum of 2°C during the afternoon. All five sensors give very consistent measurements as indicated by standard deviation values <0.09°C. During the second run excellent agreement occurred during daytime hours and greater (2–3°C) differences at night.

During the first run the performance of the single-sensor float was disappointing. Although temperature changes are in the same direction as those of the infrared thermometer, absolute temperature values during daytime are considerably higher (up to 5°C). Systematic differences between the remote and the direct contact methods can be expected. Marlatt (1967) and Malevskij-Malevich (1963) have drawn attention to reduction of surface temperature by evaporative cooling. The latter presents data showing negative temperature gradients within the upper 5 cm layer of water in an evaporation pan and quotes values as high as 1.5°C for the surface temperature reduction. Since our data represent conditions of relatively high solar heating, some degree of surface cooling by this mechanism can be anticipated. Its extent can only be postulated if we compare the Barnes and the float results assuming that the float data represent the regime slightly below the water surface. In the case of the five-junction sensor, the observed maximum difference of 2°C is consistent with the Malevskij-Malevich findings. The differences indicated by the single float are too large to be accounted for in this manner and suggest systematic error possibly due to incorrect location of the single sensor, self-heating, or to the leakage problem referred to earlier. Since there is uncertainty concerning the performance of the single float before it was replaced, these earlier data will be discarded. A better performance was obtained from its replacement. In addition to a new thermistor sensor, a larger hole had been made in the float to permit greater circulation of water and air around the sensor. Measurements were made on

29 October around solar noon when any radiation error would be at a maximum. The results (Table 4) show that the agreement is considerably better than in Run 1 and as good as the agreement between the multiple sensor float and the infrared thermometer in Run 2.

Temperatures calculated from the radiation balance, although in good agreement with the other methods at night, during both runs, show large irregular fluctuations during daytime and systematic overestimation with values as much as 12°C larger than those obtained with the infrared thermometer. Using $\epsilon=0.972$, the effect of errors in measured outgoing flux upon computed surface temperature can be determined by differentiating Eq. (9) with respect to L_0 to obtain

$$\delta T_s / \delta L_0 = [4(\epsilon\sigma)^{-1} L_0^3]^{-1}, \quad (10)$$

and solving for an appropriate range of L_0 values. Using L_0 values between 0.53 and 0.66 cal cm⁻² min⁻¹, a 1.5% error in radiation results in a 1°C temperature error. Hence, the extreme error of 12°C requires an error of 18% in the determination of the outgoing longwave flux. This is close to the upper limit of error that can be expected in the instrumental evaluation of L_0 .

From our measurement procedure outgoing longwave radiation is calculated from

$$L_0 = T_i' + \sigma T_e^4 - R_n - S_0 \quad (11a)$$

by day, and from

$$L_0 = T_i' + \sigma T_e^4 - L_n \quad (11b)$$

at night, in which L_n is the net longwave balance. Assigning sensor errors of $\pm 5\%$ to S_0 and T_e , and $\pm 10\%$ to R_n and T_i' , recorder errors of $\pm 1\%$, and integration errors of $\pm 2\%$, the rms error for L_0 determination is 16.4% by day and 15.5% at night. Since the data from the two runs show much smaller errors at night and a larger, consistently positive daytime error, a systematic diurnal source of error seems likely.

TABLE 4. Comparison of surface temperature measurements between single-thermistor float and infrared thermometers.

Solar time	Infrared thermometer (°C)	Float (°C)
1110	5.5	5.9
1245	6.5	6.4
1515	6.0	5.7

FIG. 1. Surface temperature values for 16-17 July and 30-31 July 1969.

The nature of this error can only be examined further through comparison of results from the radiation balance with the single thermistor float data.

On the basis of the results in Table 4 the single thermistor float temperature (T_s) data have been used as a control against which surface temperature evaluations from the radiation balance (T_r) can be compared over the relatively long period, 27 August to 18 November. Simultaneous evaluations were available for about 3000 half-hour periods. Initially, all data were pooled and the differences ($\Delta T = T_r - T_s$) calculated. The frequency distribution for ΔT (Fig. 2) is very close to normal, with a means of -0.5°C and a 2.1°C standard deviation. The latter statistic suggests that the large discrepancies (up to 12°C) in T_r , which were apparent during the earlier 24-hr runs, are atypical of the measured data after 27 August.

The pooled data conceal significant seasonal and diurnal trends. Visual inspection showed that from late August to mid-September (Period A) T_r values were higher for 77% of the data. Thereafter, until the end of the project (Period B), higher T_s values occurred in 65% of the data. The change-over date was arbitrarily located at 9 September. The means for ΔT are 0.75°C (A) and -0.84°C (B). A Student's test established that the difference between these means is significant at better than the 0.1% probability level. Pertinent statistics for nocturnal data are given in Table 5. Student's tests showed, first, that nocturnal ΔT values are significantly different from total (daytime and nocturnal), and hence daytime, values; and second, that nocturnal values of ΔT in Period A are significantly different from those in B. In both cases the probability level is higher than 0.1%. It seems that the diurnal trend is superimposed upon the seasonal trend since nocturnal value of ΔT in A and B, which are also significantly different, are displaced in the same direction as the total data. Data for 28 August and 25 October (Fig. 3), both relatively fine days, show the diurnal and seasonal trends quite well and also the

FIG. 2. Frequency distribution of differences between surface temperature determined from the radiation balance, T_r , and from a floating thermistor, T_s : hatched area, nocturnal data only.

general change from positive daytime ΔT values in A to negative values in B.

Diurnal variation in ΔT suggests systematic errors due to temperature or radiometer oversensitivity to solar radiation but it is not apparent how these can be reconciled with the change in sign of ΔT after 9 September. In both periods A and B, relatively large high-frequency fluctuations occur consistently in daytime. Since these are encountered on clear as well as cloudy days, internal energy balance variations due to irregular heat exchange within the net radiometers seem likely.

The ΔT turnover, however, requires a physical explanation. The following attempt is speculative since it can not be tested with the project data. Since radiation flux measurements were made at a height of 5 m above the water surface, divergence of the outgoing longwave flux within the intervening air layer may be significant.

An attempt was made to investigate the upward flux divergence term. The air layer was considered to be saturated and at a uniform temperature T_a of 20°C . Water surface temperature was varied between 10 and

TABLE 5. Mean nocturnal temperature differences and standard deviation.

Data group*	Number of observations	Mean difference ($^\circ\text{C}$)	Standard deviation ($^\circ\text{C}$)
All data			
in A and B	3285	-0.5	2.14
All nocturnal data			
in A and B	1969	-0.27	1.74
All data in A	497	0.75	1.95
All nocturnal data			
in A	261	0.93	1.56
All data in B	2788	-0.84	2.11
All nocturnal data			
in B	1708	-0.67	1.77

* Period A, late August to mid-September; B, remainder of project.

FIG. 3. Surface temperature from the radiation balance and from a floating thermistor for 28 August and 25 October 1970.

30C. From Kirchoff's law the change $dI_{S\lambda}$ of monochromatic radiation intensity incident on a thin, stratified slab of moist air is

$$dIW_{\lambda} = a_{\lambda}I_{a\lambda} - a_{\lambda}I_{S\lambda}, \quad (12)$$

where a_{λ} is the monochromatic absorptivity (emissivity), $I_{a\lambda}$ the monochromatic intensity of emission at air temperature, and $I_{S\lambda}$ the monochromatic intensity of emission at water temperature. Integrating this equation with respect to azimuth, zenith angle and wavelength, the upward flux divergence δF is given by

$$\delta F = \bar{a}\sigma T_a^4 - \bar{a}'\epsilon\sigma T_s^4, \quad (13)$$

TABLE 6. Results of radiative flux divergence calculations.

Air temperature (°C)	Water temperature T_s (°C)	Flux divergence F (cal cm ⁻² min ⁻¹)	Radiative temperature T_r (°C)	ΔT ($T_r - T_s$) (°C)
20	10	0.0218	13.0	3.0
	15	0.0130	16.7	1.7
	18	0.0075	19.0	1.0
	20	0.0041	20.5	0.5
	25	-0.0052	24.2	0.8
	30	-0.015	28.3	-1.7

where $\bar{a}$ and $\bar{a}'$ are integrated emissivities of the slab of air at the air and water temperatures. Elsasser and Culbertson (1960) have shown that the isothermal emissivities for a 2-cm slab of water vapor vary only by $\frac{1}{2}\%$ between 10 and 20°C. This is small compared with the corresponding change in blackbody fluxes of $\sim 14\%$. As an approximation, therefore, Eq. (13) can be simplified to

$$\delta F = \bar{a}(\sigma T_a^4 - \epsilon\sigma T_s^4). \quad (14)$$

Values of δF , calculated using $\bar{a}=0.23$ (Brooks, 1950), are given in Table 6. These show that the surface longwave flux (and, thereby, temperature) will be overestimated by a radiometer mounted at 5 m when $T_a > T_s$, and underestimated when $T_a < T_s$. These two regimes correspond to Periods A and B. During Period A the air was warmer (mean difference of 2.4°C) than the water for 78% of the time while in Period B it was cooler (mean difference of 0.8°C) in 60% of the instances. Differences between true water temperature and its apparent radiative temperature, which includes δF , are within the order of magnitude of the temperature differences observed experimentally. However, the calculation is likely to be an overestimate of net flux

divergence since divergence of the incoming flux was ignored. It should also be emphasized that the calculations refer to one instant. Temperature structure will vary with time depending on advection and the divergence of sensible heat in the layer. There were insufficient data to calculate these terms. We can only conclude that careful divergence studies, similar to those carried out by Funk (1960), are required over water surfaces. Apart from their relevance to physical processes in the lower atmospheric layers they could assist in defining maximum heights for locating sensors which are to be exposed to emitted surface radiation.

4. Conclusions

The emissivity of a water surface is a conservative parameter. A value of 0.97 can probably be used for Lake Ontario and the other Great Lakes and may be applicable elsewhere. Where surface temperatures are known to within a few degrees, values of calculated outgoing longwave radiation using this emissivity value will probably be more accurate than radiometric determinations with commercially available sensors. Furthermore, since reflected solar radiation is a small term and can probably be predicted with little error, the surface radiation balance may be determined quite accurately if incoming total (shortwave and longwave) radiation is known. This measurement is much easier from vessels and buoys than measurements of surface fluxes.

Attempts to measure surface temperature demonstrated the inaccuracy of using the Stefan-Boltzmann law to calculate temperature from outgoing longwave radiation obtained as a residual from the radiation balance equation. Relatively simple direct temperature

measurement using thermistor-equipped floats are preferable.

The study also shows the need for detailed micro-meteorological investigations of radiative and sensible heat flux divergences within the first few meters of the atmosphere over bodies of water such as the Great Lakes.

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